

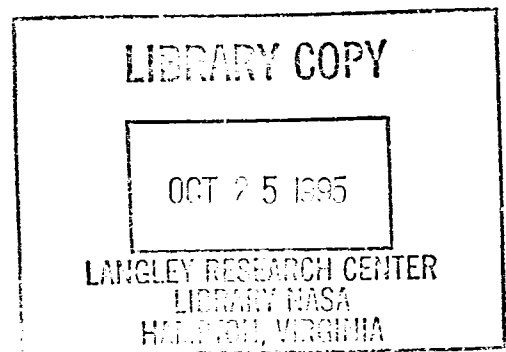


Instrumentation Development for Study of Reynolds Analogy in Reacting Flows

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Abstract

Boundary layer development in supersonic reacting flows is not well understood. A new capability has been developed which makes more extensive surface measurements practical, leading to an increased understanding of these turbulent boundary layers. The new technique provides measurements which allow the formulation of a relation between the transfer of momentum and the transfer of heat for reacting flow, similar to the Reynolds Analogy for laminar flow. An instrument has been designed and built which simultaneously measures the surface heat transfer and shear in the presence of combustion. These concurrent measurements made at the same location, combined with local flow conditions, enable a quantitative analysis of the relation between the surface drag and wall heating, as well as identifying possible ways of reducing both.

Nomenclature

C_f	skin friction coefficient
Nu	Nusselt Number
P_0	total pressure
P_r	Prandtl Number
$P_{r,t}$	Turbulent Prandtl Number
q	dynamic pressure
q_w	heat flux
Re	Reynolds Number
S	area of sensing head
St	Stanton Number
T_0	total temperature
V	free-stream velocity
ρ	density
τ_w	shear stress

Introduction

The intended application for this study is to further the understanding of the flow through the combustor of a scramjet (supersonic combustion ramjet) engine. Experiments with supersonic combustors have, until recently, focused mostly on the basic global issues of thrust measurement, fuel injection and mixing. Advances in instrumentation technology have made it practical to measure more detailed aspects of the boundary layer of this flowfield, and efforts have been made to include more surface measurements in experimental test programs.

A considerable step in understanding this high enthalpy, high heat flux environment is to formulate an analytic relation between the skin friction and heat transfer in the combustor flow, similar to the one that exists for laminar flow. Schlichting [1] defines this relation, called Reynolds Analogy, as

$$Nu = \frac{1}{2} C_f Re f\left(\frac{x}{l}, P_r\right) \quad (1)$$

where the Nusselt number Nu , the Reynolds number Re , and the Prandtl number, P_r , are related in terms of a Stanton number, $St = \frac{Nu}{Re P_r}$, which includes the heat transfer coefficient in its definition. This relation is valid for all laminar flow, and similar relations have been developed to apply to turbulent flow. However, as the flow becomes more complicated, classical Reynolds Analogy concepts become less reliable. The mechanisms present for reacting flow are not well understood because of its complicated turbulent, combusting and three-dimensional character.

The major emphasis for this project is therefore to provide a means to extend the baseline of information available for predicting drag in this reactive flowfield.

Due to the uncertainties involved in predicting this boundary layer numerically, it is most sensible to perform an experimental examination of the flow; even though this is not a simple flowfield in which to make surface measurements. Means are now available to directly measure skin friction and heat flux concurrently at the same location in this flowfield. Measurements taken of the two quantities first need to be combined with state variables and information about local flow conditions and then a quantitative analysis enables a relationship to be established between the two.

Note that the instrumentation capability developed here can be utilized in a number of other relevant flows. The technique will give further experimental validation to correlations for hypersonic flows, supersonic flows, and transition studies. The gauge is also suited for jet engine or rocket nozzle tests and in experiments exploring engine/airframe integration. Any boundary layer investigation where heat and momentum transfer are linked can benefit from a simultaneous measurement at one location. In addition, the experiments create an expanded database that is vital to new code validation. The gauge design concept is simple and versatile, such that modifications for new facilities can easily be made. The criteria for geometry and materials are based on tunnel logistics constraints and expected flow conditions.

Background

Reynolds Analogy has been a powerful analytical tool since it first appeared in the late

1800's. In its most simple form,

$$\frac{C_f}{2} = StP_r^{\frac{2}{3}} \quad (2)$$

Reynolds Analogy will hold for laminar, incompressible flowfields. It has been modified and extended to compressible and turbulent flows in various analytical and computational forms. Many investigations took place in the 1950's, comparing experimental data to existing or new theories. For example, an early analysis done by Beckwith [2] applies an integral method to extend the analogy to compressible laminar flow. Ludwig and Tillmann [3] examined turbulent flows with pressure gradients. Another analysis by Hool [4], uses the von Karman improvement to Reynolds Analogy for two-dimensional turbulent flows.

Van Driest also derived his own variable density, variable property Reynolds Analogy [5]. The law is determined from incompressible von Karman mixing-length theory with the momentum integral equation over a flat plate written in terms of temperature and flow variables. The van Driest analysis is important in that it is valid for high speed turbulent flow over a flat plate and does include cases of heat transfer, but not combustion [6]. At about that same time, Eckert [7] introduced a semi-empirical method for two-dimensional flow for a Mach number range up to 20. Using the recovery temperature, Eckert generates a solution for laminar and turbulent flow, generally agreeing with experimental flat plate measurements.

An analysis of available experimental data in 1970 [8] concluded that not enough useful data existed to allow for an empirical Reynolds Analogy definition for turbulent flows either below or above Mach 5. In addition, the data needs to contain measurements

of both skin friction and heat transfer to be used for validating prediction methods.

A very complete comparison study of the most widely used methods was done by Cary and Bertram [9] in 1974. They compared methods of Spalding and Chi [10], Coles [11], Eckert [7], White and Christoph [12], Moore [13] and van Driest [5]. The comparison was made by transforming the data to incompressible form, then comparing the transformed data with classical incompressible predictions. The results are listed in terms of which method correlated best above and below Mach 10. One of their conclusions cited Spalding and Chi as the best prediction method below Mach 10, indicating that it has a potential input for this investigation.

A similar study in Reference [14] starts with a description of experiments yielding hypersonic, turbulent boundary layer data, then compares the results to existing correlations. As in the Cary and Bertram case, the best prediction method depends on variables such as Mach number, wall temperature, Reynolds number, surface geometry and virtual origin location. The option also exists for obtaining an analogy numerically, using a variable function for the turbulent Prandtl number, $P_{r,t}$ to obtain a more accurate Reynolds analogy factor. An extended Von Karman solution using this method is described by van Driest [15]. Also, by introducing a variable function of $P_{r,t}$ into the energy equation, a law of the wall can be computed and used to define a Reynolds Analogy [16]. These approaches offer an alternative form of the model equations written in such a way as to offer reasonable relations between momentum and heat transfer in a turbulent, compressible flow. Note that the accuracy of any of these methods depends on the models for turbulence used - an ill defined subject for complicated flows.

These correlations do not address the issue of combustion which adds several new variables to the analysis. It was suggested in Reference [17] that a Reynolds Analogy for turbulent flow be used directly in supersonic reacting flow. On average, the experimental data correlates reasonably well. The current investigation provides an opportunity to add new experimental data to further investigate this concept. In addition, a recent interesting analysis has been conducted to address the issue of kinetic effects in the correlations. Woronowicz and Baganoff [20] add a new parameter to the analysis of a flat plate in terms of rarefied flow. The kinetics addressed in their analysis are also considered to be useful in the case of reacting flow.

Yet another analysis does approach the analogy in such a way as to provide specific insights for this investigation. Gaviglio [18] studied a continuous two-dimensional equilibrium turbulent supersonic boundary layer. The equations for mean momentum and total enthalpy are solved analytically, taking into account turbulent effects, with boundary conditions in terms of shear, heat flux and pressure gradient. The formulation of the solution is written in as a non-dimensional ratio, the value of which is dependent on the boundary conditions. The solution works in simple flowfields, however, the author indicates that there is not enough high temperature flow data to verify that solution. The method shows enough flexibility that adding the effects of combustion may be possible. Data, both with and without combustion, can be applied to this solution to determine its usefulness.

Current techniques in CFD are also progressing toward a possible option to obtain the correlation. Very recently, the means have been developed to address Reynolds

stress models in turbulent flow [19] such that a reasonable method for predicting Reynolds Analogy in complicated flow may now be possible.

Nevertheless, it is still not clear which of the above procedures is most relevant to the current investigation, but much depends on examination of the experimental results, as is included in every one of the above referenced discussions.

Discussion

The motivation for this project results from a need to better understand boundary layer effects in a scramjet combustor. In high speed operation, a scramjet engine produces high thrust, but due to its structure, also produces high drag, leaving a small net available thrust coming from the engine. As the Mach number increases, the change of enthalpy resulting from combustion becomes an increasingly smaller percentage of the total enthalpy, which makes losses such as wall friction and heat transfer increasingly important. The effects of surface drag actually become a significant fraction of the total engine drag at hypersonic Mach numbers, requiring a detailed knowledge of these drag properties before a successful Mach 15-20 airbreathing propulsion system can be developed.

A major consideration for proposing this specific correlation was experiencing the difficulties encountered in measuring or predicting boundary layer quantities in the supersonic reacting flow. Experimental measurements of boundary layer quantities in this flow have been the best source for design information; data collected during these experiments, with or without a correlation, have a waiting list of CFD specialists for use in code validation. The information obtained

by this new instrument is important in that more reactive flow measurements are needed for combustor design purposes while the correlations can make future measurements easier and more effective. Certainly more options exist for measuring heat flux than skin friction. It would be of tremendous benefit to the community to have a means to accurately measure combustor drag levels simultaneously with a reliable heat flux measurement.

The most direct way to look at the combustion effects on the boundary layer is to examine the measurements as a function of various flow input parameters. In a supersonic combustor, the relevant flow parameters are combustor entrance Mach number, stagnation temperature and pressure, type of fuel and injection scheme, and its corresponding fuel equivalence ratio. The relation between shear and heat transfer should be a function of axial distance from a fuel source, as well as a function of the presence of combustion. The final relation should include a combination of these variables that has been determined through a systematic examination of the effects of each on the skin friction and heat transfer along with available analytical functionality.

Heat transfer in a reactive system could be controlled by one or more of these parameters since it is uncertain if the film coefficient is strongly related to certain independent variables. A straight forward study aimed at elimination of input conditions would isolate the real driver of surface effects. Then a parameter that incorporates the most important variables could be included in a correlation formula. The corresponding uncertainty analysis determines the feasibility of extending these results to other combustor models with varying flowfields (i.e. increased Mach

number or different fuel injection). At the same time, repeated experiments with different input flow conditions uncovers circumstances under which the surface drag and wall heating can be reduced. The analysis of output is actually a progressive effort to understand all of the identifiable consequences of flow parameters on the measurement.

The facility for which this instrumentation was designed is the Direct Connect Supersonic Combustion Test Facility (DCSCTF) at NASA LaRC. This facility is capable of supersonic combustion with simulated flight conditions between Mach 4-8. A test plan would include a number of runs with nominally the same conditions, and then runs with one flow parameter at a time varied. Measurements made with the combustor in subsonic, mixed mode, and supersonic operation make the useful range of the correlation as wide as possible. In addition to varying flow conditions, the measurements need to be made in as many parts of the model as possible, since the flow changes dramatically over a short distance. For example, the shear in the nozzle is known to drop off drastically from that inside the combustor section. Optimally, several gauges should be placed in the combustor model simultaneously and measurements taken for a variety of flow conditions. This variety of measurements is also advantageous in that simply quantifying separately the subsonic flow heat flux and surface drag to the supersonic combustion results is significant in itself.

Discussions of a potential correlation began several years ago when shear and heat flux were being measured independently in supersonic reacting flow. The measurements were taken in the NASA Langley DCSCTF, with a perpendicular injection model. The heat flux was measured with a Nanmac erod-

ing thermocouple gage and the skin friction was measured (by the author) with a device similar to the one described in this report. Details of the experiments are contained in Reference [21]. Figure 1 shows a sample comparison of the heat flux and shear measured on opposite walls in the same duct, but not at the same axial location. The output is shown for shear and heat flux through the total test time. It is clear that the shear stress and heat flux are related to each other, each following the initial flow startup, igniter-on and fuel-on portions of the test. An examination of many runs shows this trend continues in every test run, but their relative effects on each other are dependent of the conditions of the flow. The preliminary analysis indicated that a correlation of these quantities exists that can be defined in terms of flow variables and that injection type and fuel equivalence ratio are ostensibly significant factors in this correlation.

Gauge Design

The configuration chosen was a floating wall element gauge that has been specifically developed for directly measuring skin friction in the boundary layer of a high enthalpy, high heat flux flowfield [21]. The design is based on the concept that the cantilevered floating element, when situated flush with the flow surface, generates an output which is proportional to the local shear. The floating element responds to shear from the passing tangential flow. The cantilever supporting the floating element bends slightly due to the shear and the deflection is registered by a sensitive, non-contact, displacement transducer.

As always in a floating element design, the cantilever beam geometry is chosen based on the expected shear forces. With the expected

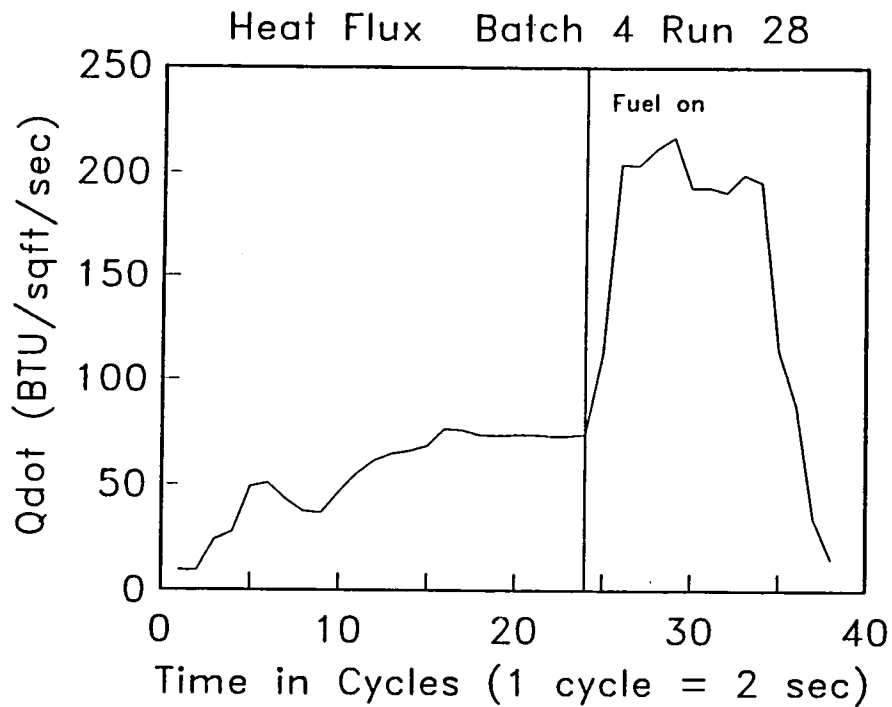
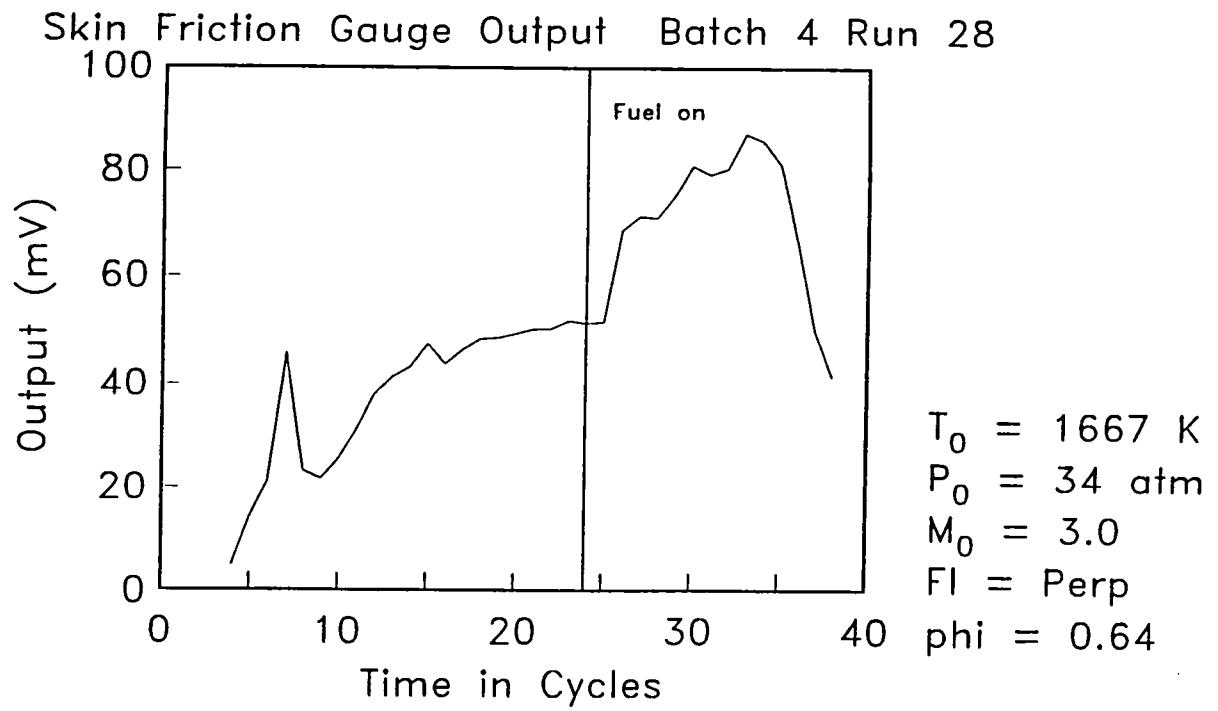


Figure 1: Skin Friction and Heat Flux Output - Test Cell 2

forces known, a cantilevered beam deflection study optimizes the beam in terms of length and shape. While the cross-section of the floating element is round, the cross-section of the deflecting beam is rectangular on the outside. This is achieved by wire cutting the beam from a solid thick diameter. The wire cutting starts right below the floating element and stops before the bottom of the beam. The concept is illustrated in a three-dimensional sketch in Figure 2. The purpose of wire cutting the beam is to leave only a small total volume underneath the floating head. Note that the wire cutting allows the entire centerpost to be machined of one continuous piece. This eliminates breaks in the material, the possibility of the beam coming apart, and provides a continuous heat flow path away from the flow surface. A circular hole through the center of the deflecting beam is obtained by drilling a lengthwise hole through the center of the beam. The hollowed cylindrical center makes it possible to add the heat flux sensor at the top of the floating element.

A sketch of the entire gauge appears as Figure 3, showing the transducer plug, the housing and the internal centerpost. The cantilever mounts inside the housing and is sealed with an O-ring on the bottom flange. The sensor is also sealed to the housing with an O-ring. The housing shape was chosen to provide a flange and bolt pattern that would accommodate an existing opening in the test cell duct. Note that a 0.476 cm (3/16 in) diameter copper tube for water cooling is embedded on either side of the post. High pressure water running through these tubes during a test insures a constant temperature of the sensor. A photograph of the three gauge components and the tip of the displacement sensor is shown in Figure 4.

The current final design has a beam length of 7.938 cm (3.125 in), which produces an anticipated beam deflection of 0.00254 cm (0.001 in). The wire cut slot is 0.0305 cm (0.012 in) wide and the circular hole drilled through the center is 0.198 cm (0.078 in) in diameter. The diameter of the floating element is 1.557 cm (0.613 in) for several reasons: first, the element should be as small as possible while having enough area to provide a force acting on its surface large enough to be registered by the deflection sensor, and second, the element should be small enough to be insensitive to flowfield pressure gradients that cause a moment across the surface of the element and affect the beam deflection. Typical pressure gradients observed in similar combustion experiments are small enough over the length of the floating element for the current gauge to produce a negligible effect.

A gap around the floating element of 0.01524 cm (0.006 in) was appropriate for minimizing errors caused by the presence of the gap. The specific geometry of the floating element is always an important design consideration, because the gap around it can introduce various errors at the surface [22]. The geometric issues in floating element design that control misalignment effects are the gap to diameter ratio, and lip to diameter ratio. An experimental analysis was performed by Allen [22] where the geometry was systematically varied to determine which combinations are best for reducing effects of the gap. In addition, he addresses protrusion and recession of the floating element. Consistent with Allen's results, this design incorporates a lip to diameter ratio of 0.0326, a gap to diameter ratio of 0.0098, and is insensitive to protrusion/recession for vertical misalignments of less than 0.0076 cm (0.003 in).

A high viscosity silicone oil surrounding the

CENTERPOST GEOMETRY

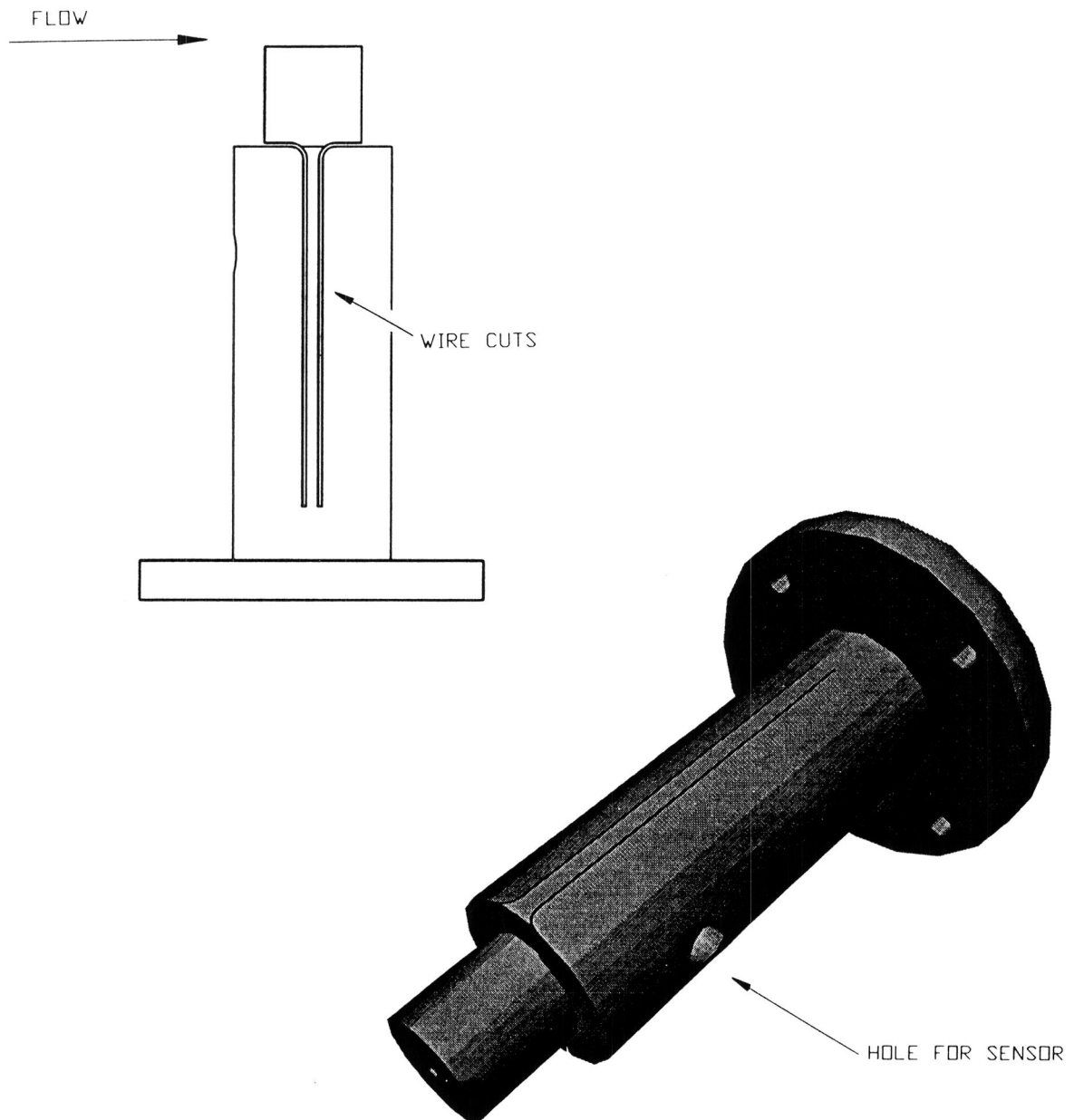


Figure 2: Sketch of Skin Friction Gauge Concept

SKIN FRICTION/HEAT FLUX GAUGE DESIGN FEATURES

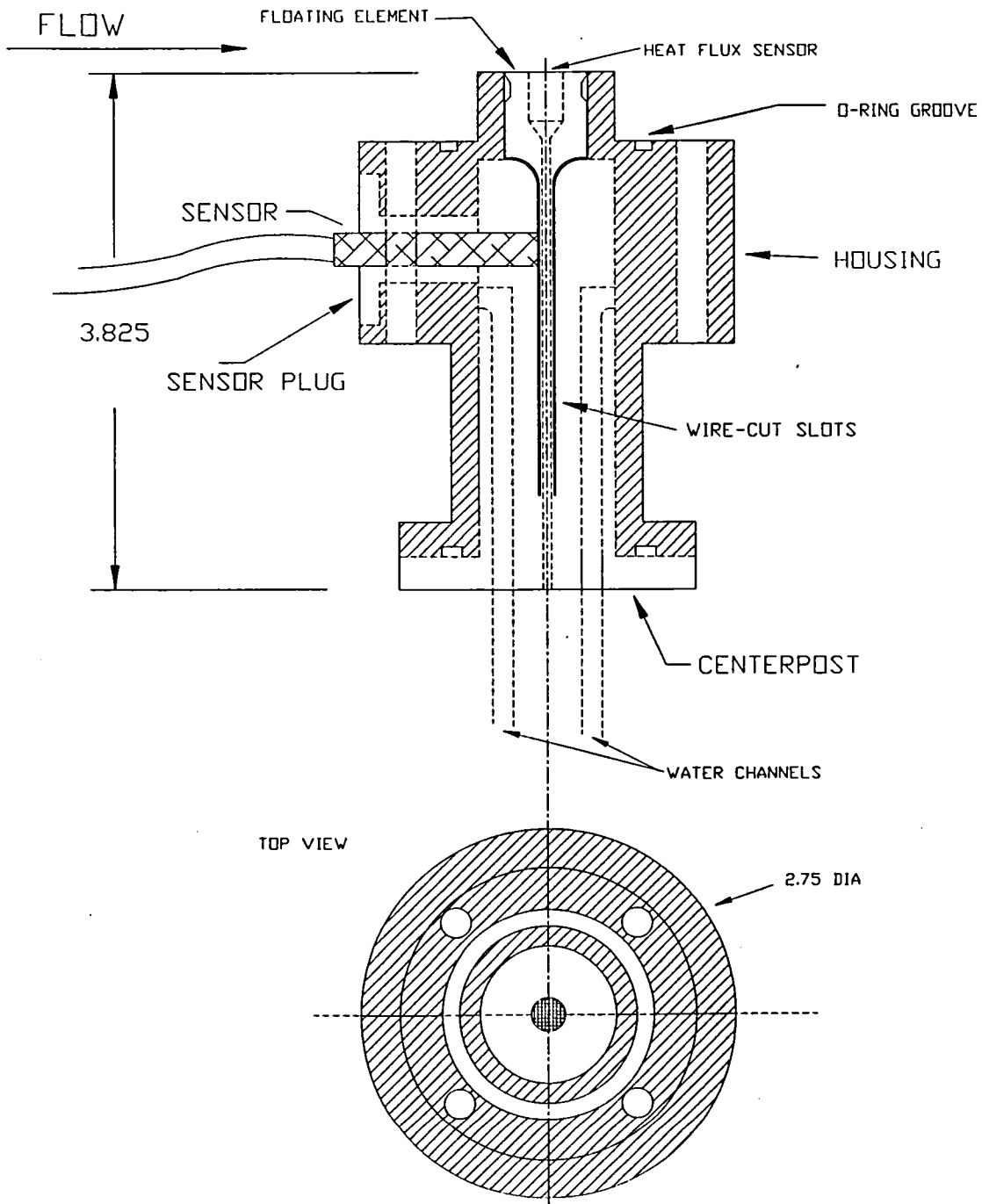


Figure 3: Skin Friction Gauge Design Features

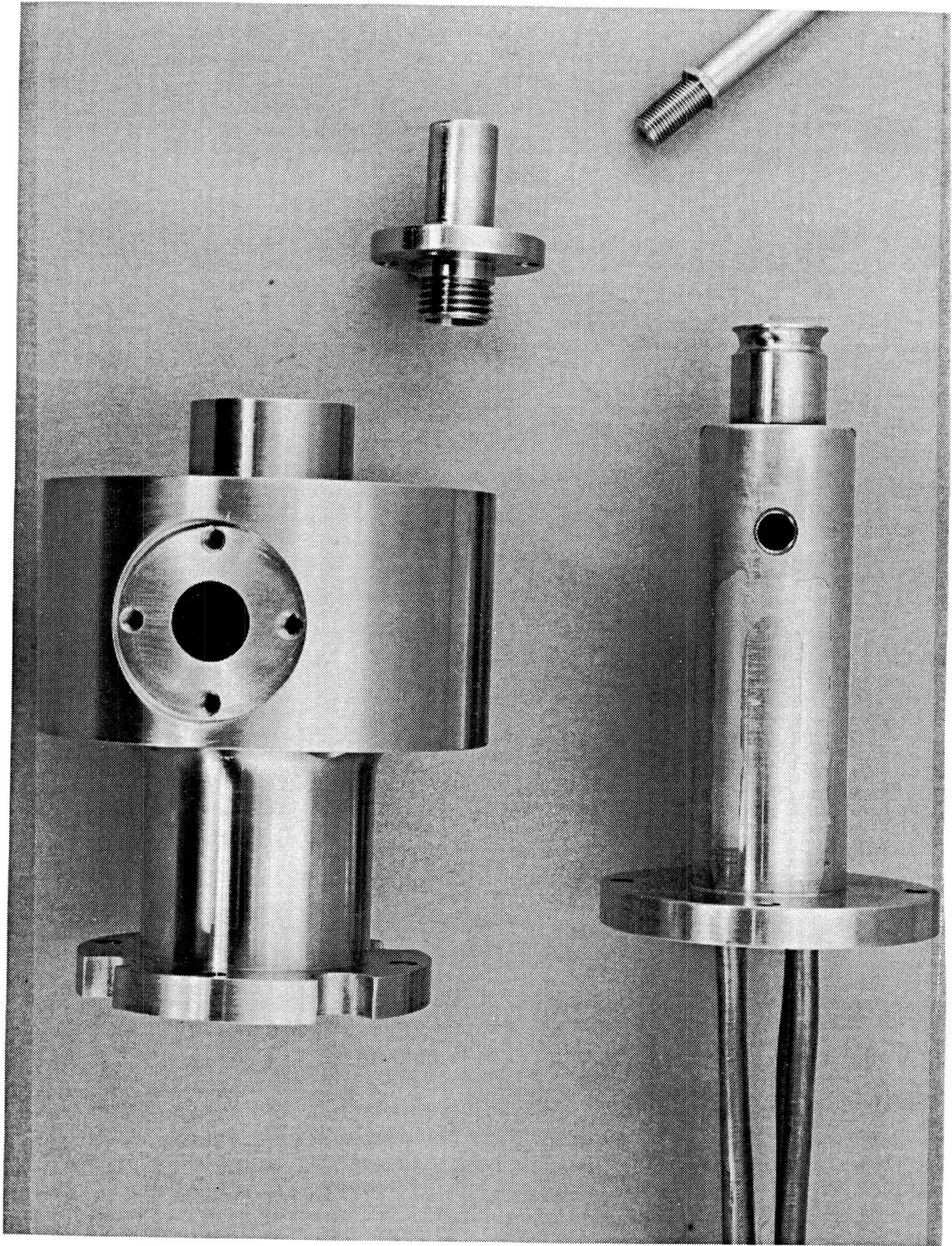


Figure 4: Skin Friction Gauge Housing, Centerpost and Sensor PIUG

centerpost inside the housing serves several purposes. First, the presence of a liquid in the cavity of the gauge minimizes any pressure differential below the surface by filling the gap and provides a more continuous flow surface while eliminating pockets of air underneath the sensing head [23]. Second, the liquid and the small gaps in the gauge combine to produce strong damping that limit the effects of vibrations which can be severe in scramjet tests. Note that this device, once assembled, is not delicate. Special handling of the instrument is not required. The monolithic steel structure of the centerpost leaves the gauge impervious to normal forces on the floating element. The transducer is also protected in that there is no way to deflect the beam into it. The maximum sensing head movement is only the width of the gap between it and the surrounding gauge housing which would not occur under expected flow conditions. Nonetheless, the physical stop is a good safety feature should the floating element get hit by a starting shock or other large vibrational disturbance.

Note also that the gauge must be non-intrusive below the flow surface as well as at the surface. The potential exists for the local skin friction to be greatly affected by a difference in temperature between the floating element and the surrounding wall. The details of a quantitative analysis in Reference [21] show that a step increase in temperature on the surface of the gauge of 50 K can increase the C_f on the order of 5%. The sensing head, therefore, should be tailored for each facility to which it is introduced, since common material is essential for the head to simulate the surrounding tunnel wall conditions, match the heat flow pattern, and not become a catalyst for the reacting flow. The direction of the heat flux through the gauge

is influenced by the thickness and geometry of the tunnel wall. Any significant change in temperature at the sensing head with respect to the rest of the wall alters the heat flux characteristics from the flow to the sensing head and ultimately detracts from the ability of the gauge to measure the actual wall skin friction. Implicit in this is that the sensing head surface temperature remain the same as the surrounding tunnel wall, regardless of the presence of internal wall cooling; this includes taking into account material changes introduced to the floating element by the heat flux sensor.

The final gauge design was analyzed computationally to insure that the floating element with the heat flux sensor installed did not alter its overall temperature with respect to the rest of the wall. A conduction code called CONDUCT, written by S. V. Patankar [24] proved to be useful for this application. The code provides an approximate numerical solution to the unsteady heat conduction equation where the output is the temperature at each grid point. The results from this code showed that the size, shape and material of the floating element produce a heat transfer compatible with that of the surrounding wall.

Displacement Transducer Testing

The transducer plug was made adaptable to the two different displacement sensors being considered for the experiment. The first transducer tested was the Kaman Instruments KDM-8200 Displacement Measuring System. A 1U2 model inductive bridge sensor of 4.7 mm (0.187 in) diameter registers a change of position for a conductive target over a 0.101 cm (0.04 in) measuring range. The sensor plugs into the position measurement module which converts the signal to voltage. The standard output is 0-5 Vdc for

the full calibration range. However, the original configuration of the Kaman signal conditioning system did not provide enough sensitivity. A new circuit was added to the system which significantly improved the performance of the sensor in the 0.0254 cm (0.01 in) displacement range. The displacement detection was then more than adequate, but early testing with the system uncovered a serious temperature sensitivity; the output changed if the temperature anywhere in the system circuit changed.

The second transducer considered for the gauge was a Philtec 88N2 fiber-optic displacement transducer. The sensor works by detecting the intensity of light reflected from a target surface. A group of transmit and receive optical fibers are mixed together in a geometrical arrangement at the sensor tip. The tip has a fiber bundle diameter of 0.159 cm (0.0625 in) with an overall diameter of 0.635 cm (0.25 in). Its full calibration curve is shown in Figure 5. This particular sensor is most sensitive in the near region (close to the target) of the calibration range, and was tested specifically for reliability in this range. The near region has a linear detection range of 0.0038 cm (0.0015 in) with a corresponding voltage output response of 2 volts. The sensor performance agreed with the specifications of the manufacturer.

After the experience with the Kaman transducer, the response of the fiber-optic sensor to a specified temperature change was also studied. A controlled oven test showed (see Figure 6) that for a given distance from the target, the output from the sensor decreases as the temperature increases for the range of temperatures between 33 and 52 °K (90 and 125 °F). The output is relatively stable below and above these temperatures. During testing, the sensor will be kept at a

constant temperature (below 90 °F) by high pressure water running through the cooling tubes on the centerpost.

Both transducers were used in the first series of supersonic combustion tests. It was apparent that the Kaman sensor was unreliable due to the effects of temperature changes, even though the system was isolated as much as possible from the heat source. Further testing revealed that the wiring also had to be isolated from even normal room temperature changes, which was impossible because the cable was 30 ft long. Fortunately, the fiber-optic sensor was found to perform far better in all test conditions and has been used for all subsequent experiments.

Description of Heat Flux Sensor

Three methods were used for measuring heat flux. The first method consisted of a coaxial thermocouple mounted in the center of the floating element. Knowing the properties of the material and assuming a one-dimensional flow through the wall perpendicular to the flow, the thermocouple reading from the surface could be inverted to obtain the heat flux. For this method to be successful, the thermocouple tip had to be made consistent with the material of the rest of the test setup in order to give the most accurate temperature reading. However, after installation, the thermocouple stiffness interfered with the movement of the cantilever, so this idea was dropped. In the second method, a small thermocouple plug was inserted at the top of the floating element with a flexible lead wire going down the center of the cantilever. The small type K thermocouple wire was held at the surface by a tapered plug made of chromium-aluminum, the type K thermocouple material. This arrangement worked much better.

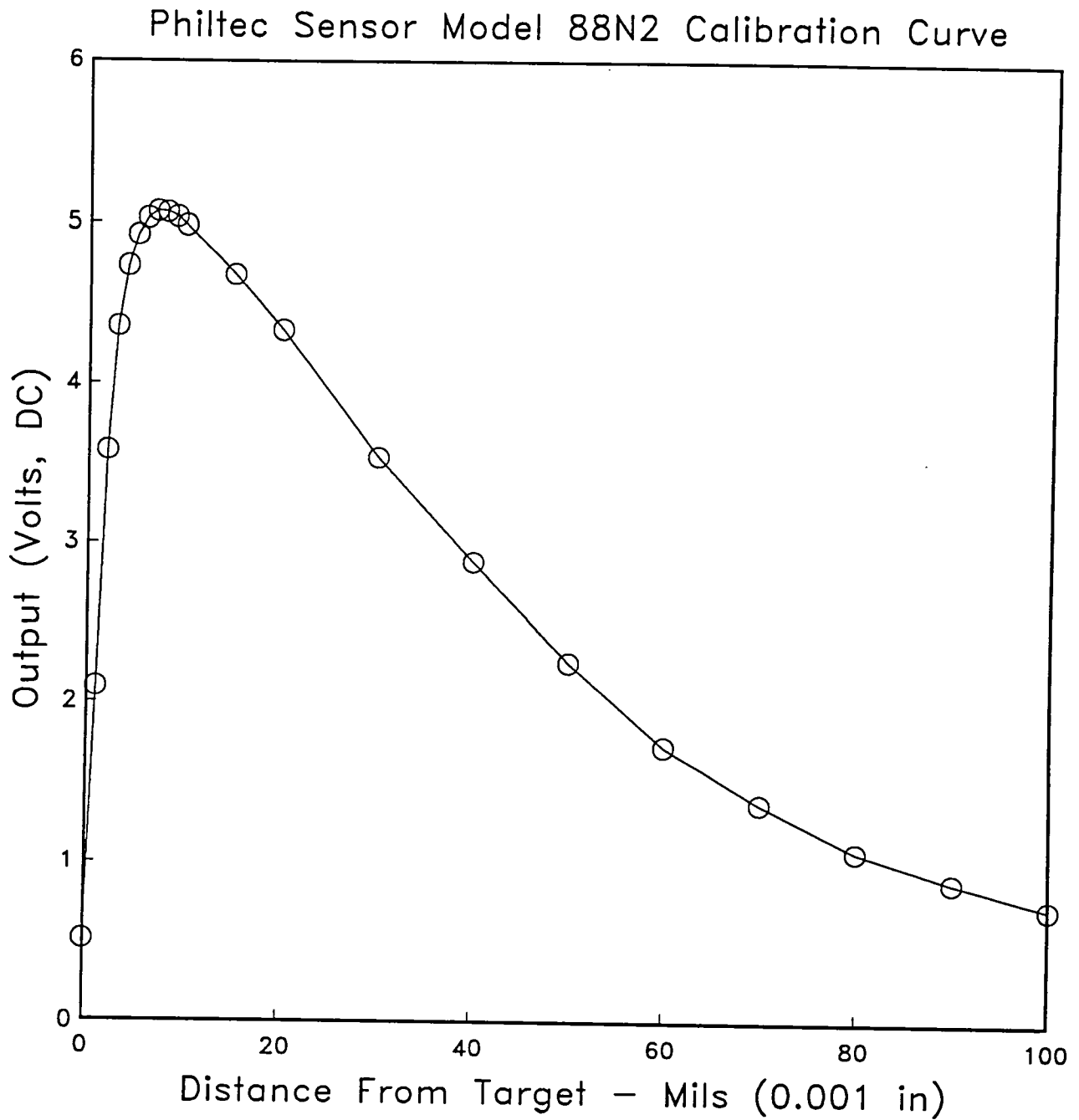


Figure 5: Philtec Fiber-Optic Transducer Calibration

Philtec Sensor Model 88N2 Temperature Calibration

Voltage Shift Due to Temperature

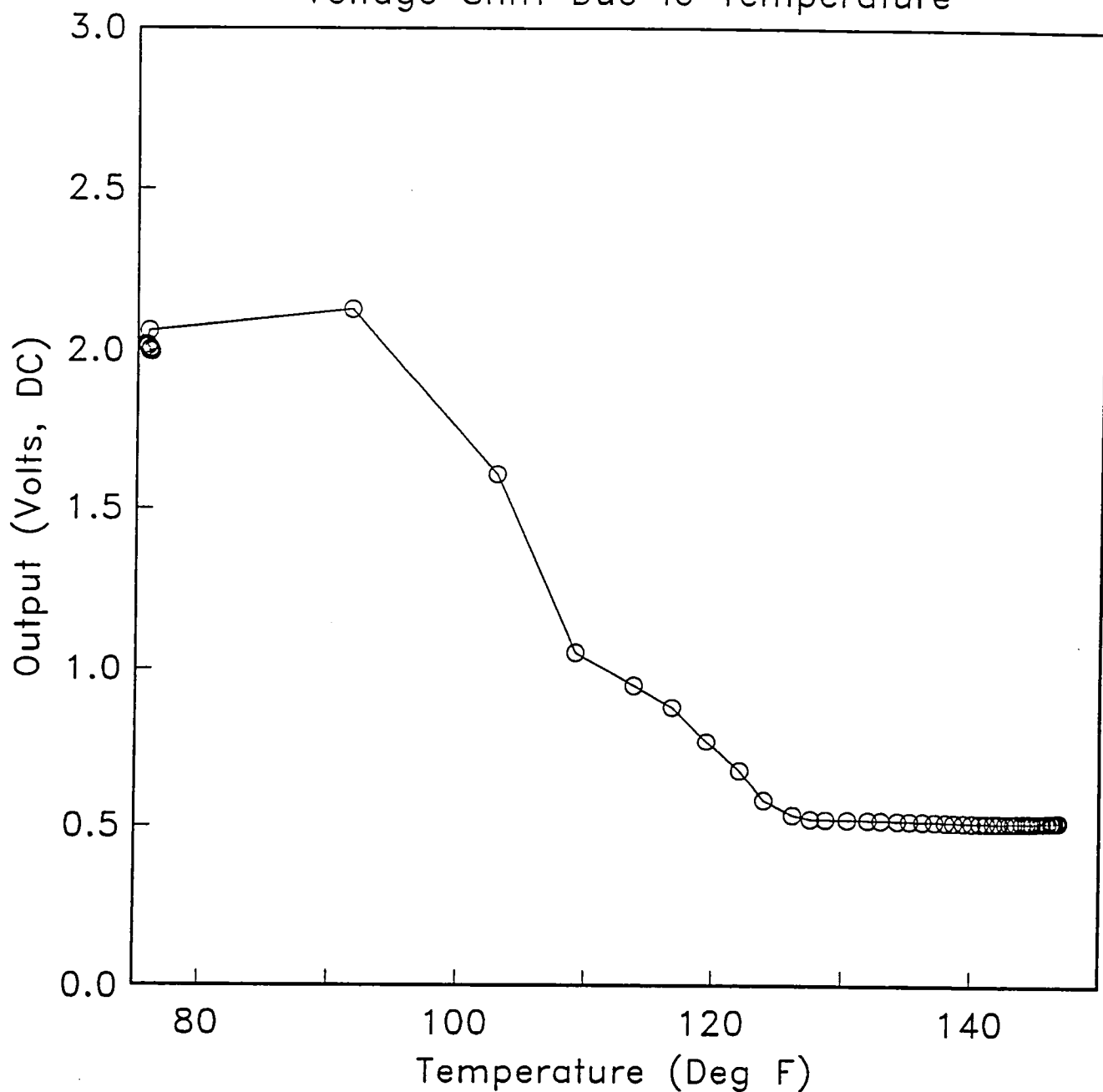


Figure 6: Philtec Displacement Sensor Temperature Sensitivity

The third method incorporated a much more sophisticated sensor for the heat flux measurement. A Heat Flux Microsensor (HFM), model HFM-6A-AIN-D, was obtained from Vatel Corporation. The microsensor consists of a thin thermal resistance layer sandwiched between temperature sensors. To amplify the signal coming from the differential temperature, many thermocouple pairs are fabricated across the thermal resistance layer to form a differential thermopile [25]. A drawing of the overall pattern overlay and a blow up of the individual thermocouples are shown in Figure 7 from Reference [26]. The thin film pattern is deposited on an aluminum nitride substrate. The microsensor measures voltages for instantaneous heat flux and temperature simultaneously. The microsensor is connected to an amplifier box which magnifies the signals to a measurable voltage. These two inputs, together with the gain on the amplifier, combine to give a heat flux value in watts/cm. The calibration equation supplied with the HFM is

$$q_w = \frac{(Volt)10^6}{(Gain)B} \quad (3)$$

where

$$B = 0.0182T + 3.671 \quad (4)$$

and

$$T = 15390 \cdot \frac{(Volt)}{(Gain)} \quad (5)$$

In these equations, T is temperature, $Volt$ stands for voltage output from the heat flux sensor, and $Gain$ means the preset gain on the amplifier box. The maximum long term temperature limit for the HFM is 1073 °K (1931 °R), with a short term limit of 1473 °K (2651 °R). No known limits exist in either direction in terms of heat flux measurement capability. An earlier version of the HFM

was actually tested in the NASA LaRC DC-SCTF at wall temperatures of up to 1000 °C (1900 °F) and compared to standard Gardon gage data. The measurements were taken at the same axial location, although on different walls [27]. The heat flux output from the two gages compared well at a heating rate of 180W/cm² (200BTU/ft²/sec), demonstrating successful operation of the HFM in heat fluxes in the range for which this gauge has been designed.

Calibration Procedure

A standard, direct force measurement procedure was used for calibrating the skin friction gauge. The gauge was clamped just off vertical, so that by hanging the weights directly on the sensor head, the sensor was pulled in the streamwise direction. Outputs were read in millivolts (mV). The applied weights ranged from 3 to 20 grams. It was very important that the signal return to the same zero after each of the weights was removed. In this respect, the gauge response was repeatable within the drift tolerances. This drift was studied carefully, and was found to be less than 3% of the total expected signal.

A sample calibration curve for the gauge is shown in Figure 8. The gauge has been calibrated from 0 to 20 grams, with the expected range being from 3 to 10 grams, depending on flow conditions. This gauge configuration can accurately describe shear stress up to a load of 30 grams, which in terms of force is 1400 N/m² (30 psf). A least squares fit of the calibration data was performed, and a standard deviation of 0.04 was found. The low value in comparison to the expected signal indicates that the calibration is highly linear. In all cases, the presence of oil in the gauge did not affect the calibration, although

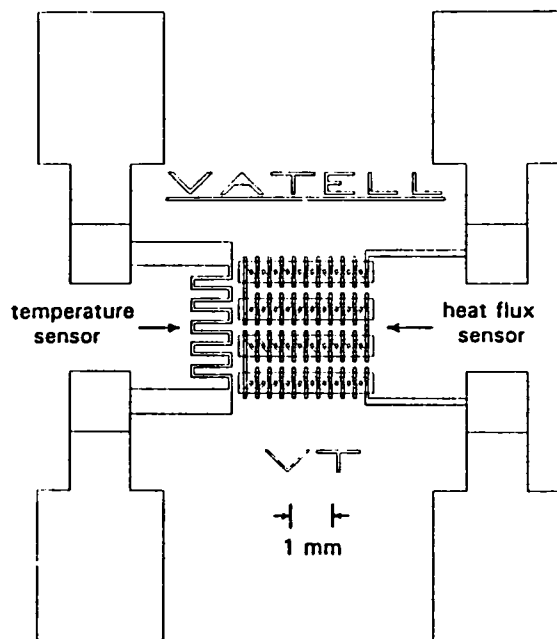
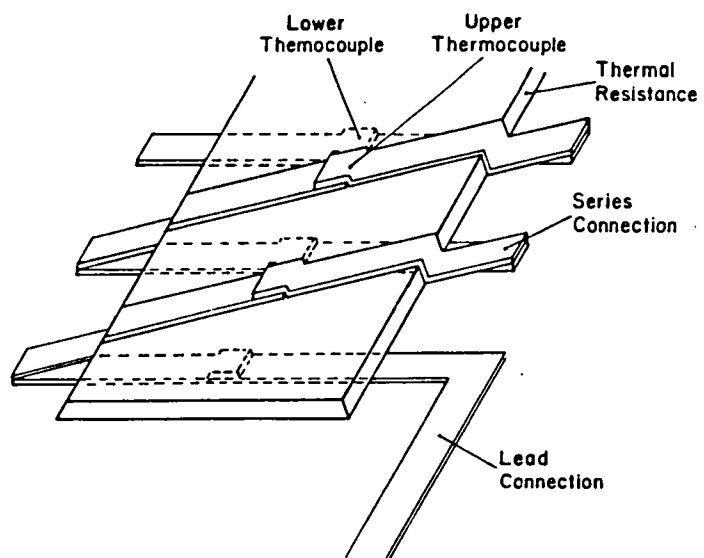


Figure 7: Heat Flux Microsensor

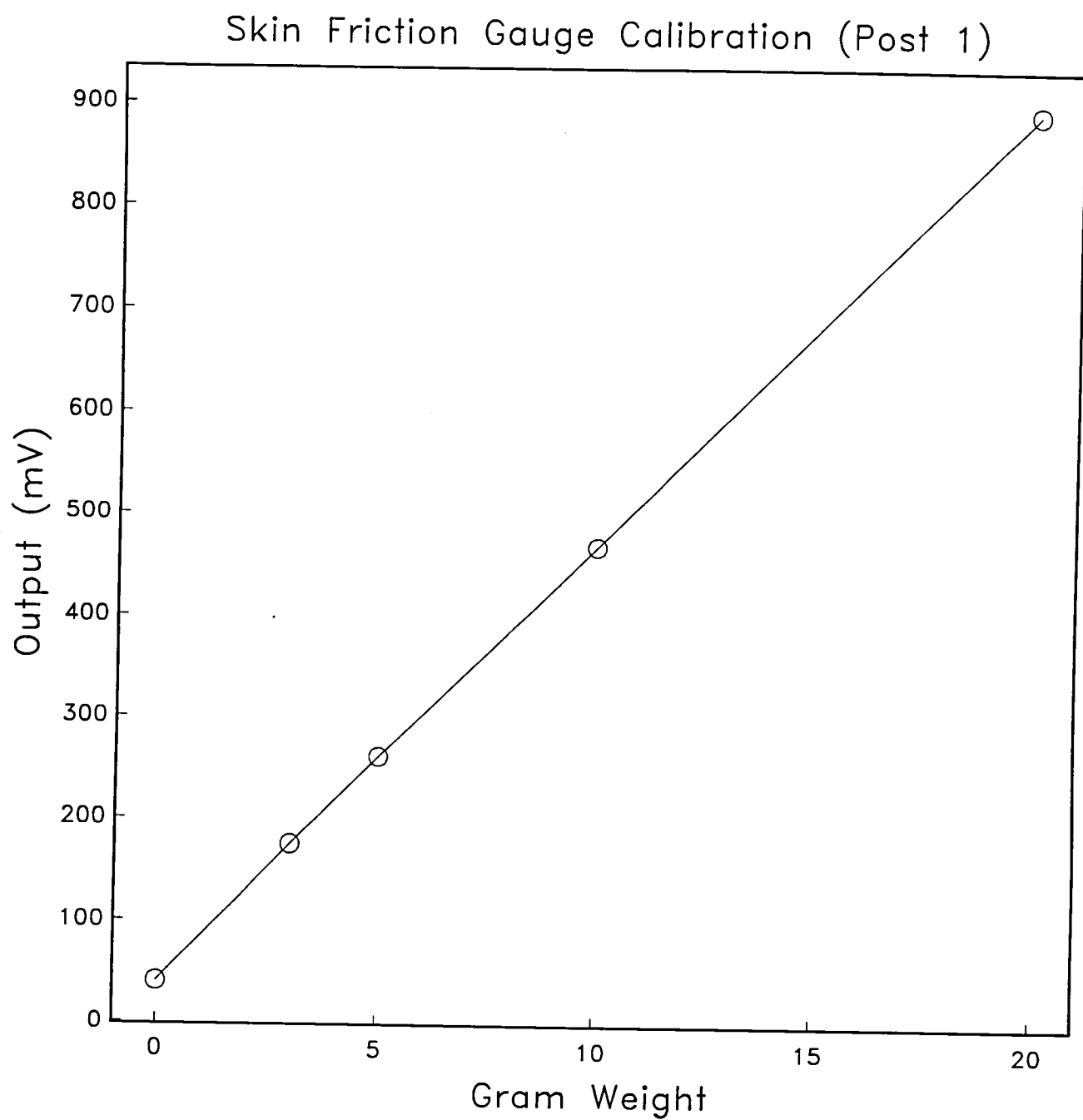


Figure 8: Gauge Calibration Curve

oil slowed down the response time. The frequency response of the gauge with oil in it was relatively low, on the order of 2-3 Hz; however, this response is enough to capture the distinct changes in shear caused by changes in test variables, such as fuel input to the flow. The gauge registers a constant output value as long as the shear maintains a steady level for more than about two seconds.

Vacuum/Pressure Tests of Displacement Sensor

In general, a supersonic blowdown wind tunnel undergoes severe changes in pressure during startup and shutdown. It is important to insure that the skin friction gauge transducer output is not affected by the ambient pressure level. In some cases, the gauge can experience the pull of a nearly full vacuum at tunnel startup. To test for the output sensitivity, the fiber optic transducer was mounted in a pipe cap so that the wires ran outside the pipe. The pressure tube was pumped up to 2.05 atm (30 psia) and a total change of 10 mV was noted. This output change is small compared to an expected 500 mV test signal. The result of pulling a vacuum on the tube was similar, again indicating that the transducer was not overly sensitive to pressure changes.

Once the gauge is completely assembled, the internal volume left by the wire cuts is filled with silicone oil, enhancing the heat transfer away from the centerpost. The high viscosity oil also minimizes the leakage of oil out of the 0.0152 cm (0.006 in) gap around the sensing head. Then, before any tests are run, the gauge is placed in a vacuum chamber, and then the pressure brought down to 0.068 atm (1 psi) to force any trapped air bubbles inside the assembly to rise and be replaced with oil from a reservoir sitting on top

of the sensing head. Removing air bubbles prevents problems with oil ejection during supersonic tunnel starting.

Vibration Tests

Significant vibrations of the test facility could add noise to the gauge signal, adding uncertainty to the output, and in the extreme, could completely wipe out the shear output of the gauge. Testing the gauge components specifically for vibration response eliminates a source of uncertainty in the measurement, and identifies the type of vibration that most affects the output of the transducer. The vibration test was conducted using the fiber-optic sensor mounted inside the housing.

The natural frequency of the cantilever and the housing was determined by mounting the gauge on a shaker table and stepping through frequencies between 0 and 10,000 Hz in the normal and orthogonal axes. In the orthogonal axis, the natural frequency of the cantilever centerpost was found to be approximately 350 Hz, and in the normal axis, it was approximately 3100 Hz. The transducer responded only to the orthogonal vibration. To aid in minimizing the effects of vibration, the prototype gauge was filled with a high viscosity silicone oil which was vacuum pumped through the gap.

Definition of C_f

Skin friction coefficient is defined as

$$C_f = \frac{\tau_w}{q} \quad (6)$$

where the shear stress, τ_w , is obtained directly by taking the measured force and dividing it by the area of the sensing head, $S = 1.904 \text{ cm}^2$ (0.00205 ft^2). The dynamic pressure, q , obtained by analysis of flow conditions, is

$$q = \frac{1}{2}\rho V^2. \quad (7)$$

The shear stress is ratioed directly by the dynamic pressure to obtain the non-dimensional coefficient, making q an important calculation. The dynamic pressure value most desirable to use comes from the local boundary layer edge conditions at the axial location of the measurement station. Direct measurement of the flow at the boundary layer edge is generally not possible due to the extremely high temperatures found there. So, to get q requires an analysis of the specific combustor geometry. The NASA Langley code called COMBAN for COMBustor ANalysis analyzes the flow as one-dimensional, or quasi one-dimensional, in that an area distribution must be specified. For this code, multi-step, one-dimensional calculations are made using real gas thermodynamic properties for a reacted fuel distribution consistent with the input parameters such as pressure distribution, geometry and fuel flow rates. Outputs include local velocity, pressure, density, temperature and Mach number at each axial location along the duct. Note that the value of C_f is only as accurate as the value of q used to non-dimensionalize it. A more complete three-, or even two-dimensional analysis of the combustor geometry and flowfield would add to the accuracy of the predicted local flow properties. Paradoxically, it turns out that these measured skin friction values are a great help in verification of the boundary layer codes that can be used to analyze this flowfield.

Cold Flow Experiment

As a first step, it is important to demonstrate that this skin friction gauge operates

well in cold supersonic flow, where it is possible to determine if the level of shear being measured compares favorably to known results. This simple experiment provides a good opportunity to correlate the output of the gauge with known theoretical predictions for flow over a flat plate. The test also underlines the adaptability of the design to flowfields other than that of supersonic combustion.

Tests were conducted in the Mach 4 Blow-down Facility at NASA LaRC. Nominal input conditions for this test are a Mach number of 4.03, a total temperature, T_0 , of 300 °K (510 °R), and a stagnation pressure, P_0 , of 13.6 atm (200 psia). The gauge was filled with a silicone oil which had a viscosity of 100 cSt. A calibration was completed as described earlier. Data were recorded using a Snapshot Storage Scope PC data acquisition program during a tunnel run time of approximately 30 seconds. A sample output is shown in Figure 9. Upstream dynamic pressure for these test conditions was calculated to be $q = 101745 \text{ N/m}^2$ (2125 psf). This gives a streamwise $C_f = 0.00140$. The corresponding flat plate prediction was computed using Program EDDYBL [30]. The program applies to attached, compressible, two-dimensional or axisymmetric boundary layers. The turbulence model used was the Wilcox two-equation $\kappa - \omega$ model. The code, run with a turbulent boundary layer right from the leading edge, outputs a streamwise coefficient of 0.00121 at the gauge location. Consistent with this result is the output of Van Driest II which also gives a coefficient of 0.00121. The discrepancy between the calculated and measured values of 15% is within the accuracy expected in this experiment. In cold supersonic flow, the dynamic pressure is lower and the gauge is not operating in its

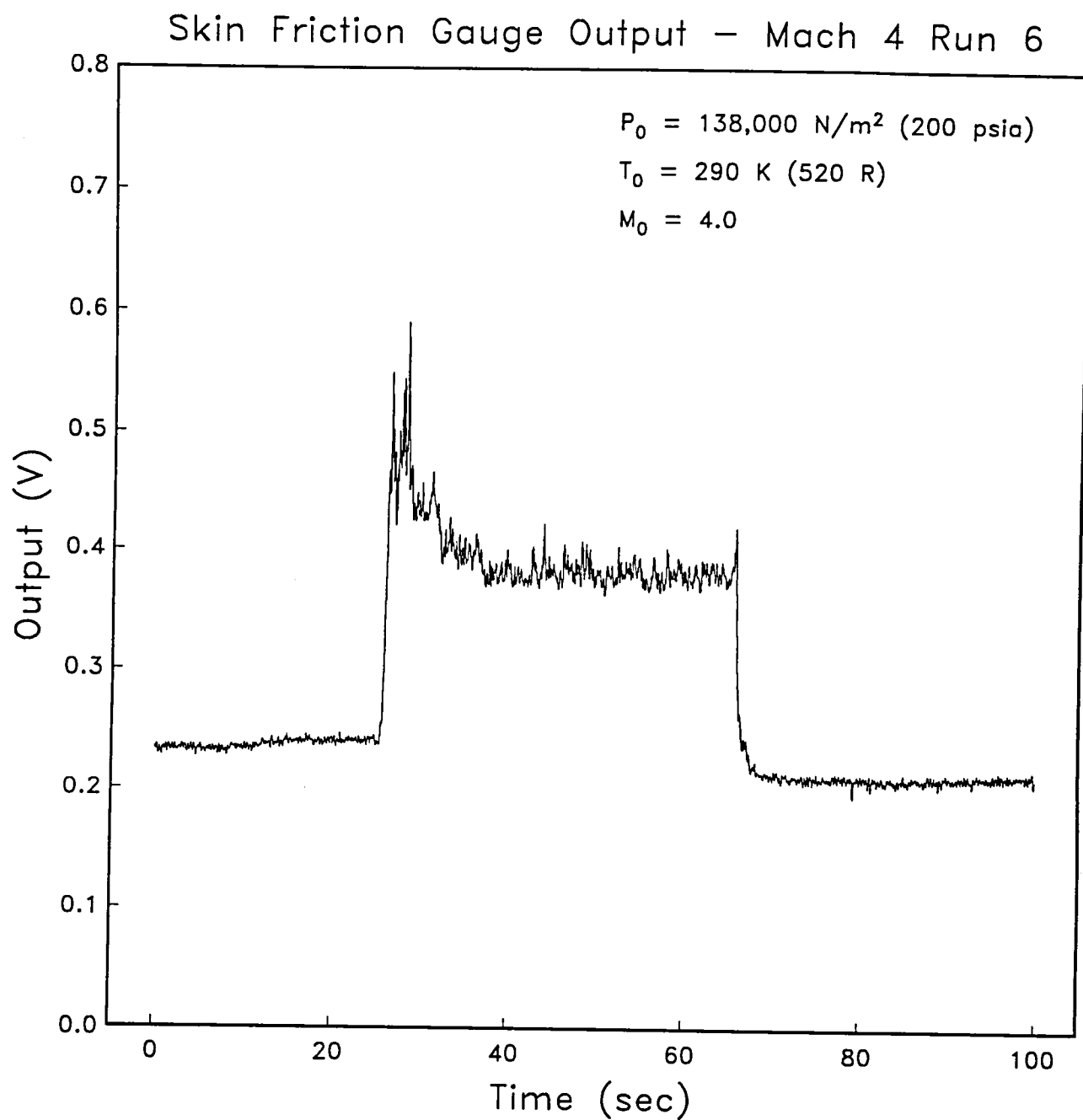


Figure 9: Cold Flow Output

most sensitive range. Also, schlieren images taken during the runs show a slight expansion wave on the tunnel ceiling above the boundary layer plate which may or may not have an effect on the flow preceding the gauge. Temperature sensitivity of the sensor was naturally suspected, but thermocouple readings on the gauge taken before, during and after the runs show that the sensor output is not affected by the approximately 10 deg temperature delta it sustains.

The information learned from this experiment is not important in itself, as many other techniques have been used successfully to measure flat plate skin friction. What is important is that the ability of the gauge to give a consistent result in a well understood flow environment, extends more credibility to the gauge results for the less simple cases, namely the supersonic combusting flowfield. The good correlation to flat plate cold flow becomes especially important when the gauge then produces a result in the supersonic combustion that is not congruous with traditional views on the subject.

Summary

A technique for measuring skin friction and heat transfer simultaneously in a high enthalpy and high heat flux environment has been developed. The purpose for making these measurements is to increase our understanding of the mechanisms which influence the boundary layer in reacting flow. The instrument configuration is a floating element, cantilever beam skin friction gauge with a thin film heat transfer gauge mounted in the top of the floating element. In preparation for hot flow tests, the gauge has undergone numerous tests of its components, including testing the transducers, then testing the

gauge in a known flowfield and comparing test results to theory. The cold flow supersonic test results match predictions for flow over a flat plate, reinforcing the validity of the results for hot tests.

Although the gauge was designed for the strut rocket flowfield, the concept is easily adapted to other flowfields where heat and momentum transfer are being studied. However, due to the necessity for keeping the gauge surface temperature the same as that of the surrounding wall, it is not possible to build a "generic, one size fits all" gauge. Each gauge configuration must be adapted and fabricated special for each test facility to account for differences in expected heat flux from the flow and the heat flow path through the wall. Fortunately, redesigning the gauge is relatively straight forward, since the basic design is flexible and can easily be adapted to facilities with other flow and logistical requirements. The parameters that need to be known for the design are those which directly affect the magnitude and direction of heat below the flow surface, including geometry, materials, cooling, physical orientation and flow conditions.

In addition to providing useful information for correlating the measurement quantities, the gauge would be useful in experiments exploring combustor drag reducing concepts such as cavity bleed and film injection. Since injection type has a significant effect on the wall properties, various schemes should be considered. An important factor in this discussion would be the adverse pressure gradients resulting from combustion at high Mach number with mass addition that affect the boundary layer and thus the heat transfer. The data that this gauge provides is also valuable in other applications including hot external flows, and jet or rocket nozzle flow.

In general, very little work has been done to study conditions inside the boundary layer of high enthalpy, high heat flux flowfields. Much more emphasis needs to be placed on all surface measurements, not just skin friction and heat transfer.

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